Petrology, Geochemistry and Geochronology of Paleozoic Granitoids and Metamorphic Rocks in Mandakh Subduction Zones, Southeastern Mongolia

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Chapter I. Introduction

The territory Mongolia is central (heart or key) part of the Central Asian Orogenic Belt, and foreign and local researchers believe that Mongolia can be well field laboratory of Central Asian Orogenic Belt. This enormous growth of the continental crust had evolved over about 800 Ma, from the late Neoproterozoic (ca 1.0 Ga) to the late Mesozoic (250 Ma), is comprised of variety tectonic units, including ancient island arc-back arc systems, ocean island, accretionary complexes, ophiolites, passive margins, and Precambrian microcontinental fragments (Khain et al., 2002; Jahn et al., 2004). Mongolia land is separated by a tectonic boundary along the Main Mongolian Lineament which Central Asian Orogenic Belt into northern and southern (Badarch et al., 2002, 2005; Windley at al., 2004).

Mandakh investigation area is located the southeastern part of the Mongolia, which is consist of Paleoproterozoic to Mesozoic that is named Paleozoic various rock types. That is why this study area is good explanation area of southeastern Mongolian geodynamic history farther it would be explain tectonic setting of Central Asian Orogenic Belts. Previous researchers could not lead to one hypothesis of Carboniferous geodynamic evolution of the south Mongolia, CAOB. This area's characteristic is that there is island-arc possibility coincide with the continental arc and post-accretion magmatism and Meso-Neoproterozoic metamorphic rocks may be relict of Tarim (South Korean) craton or correlate with Lake Zone in Western Mongolia. Furthermore, Meso-Neoproterozoic metamorphic rocks, are really poor studied and key part of unknown ancient microcontinent within in the CAOB, is found in the southeastern part of this study area.

This thesis highlights, the first time establish P-T condition and absolute age analysis of the KhutagUul and the Norovzeeg metamorphic complexes, some age data lacked geochronological data of volcanic rocks and plutonic rocks.

Chapter II. Petrography and geochemistry analysis of magmatic rocks in the Mandakh area.

The purpose of this chapter is to provide current understanding of the tectonical and geological settings, outlines of the earlier studies, lithostratigraphy, structure on the basis of field observations, surface outcrops. The Mandakh area in through the Gurvansaikhan-Mandalovoo terranes based on Mongolian tectonic classification of Badarch et.al. (2002). These southern terranes in Mongolia are divided by large sinistral Gobi-Hinggan fault. the Gurvansaikhan terrane is situated 600x250 km triangular shaped in south part of this fault, while Mandalovoo is long (<100 km) and narrow terrane. The Zuunbayan fault zone cuts obliquely across the arc and forms southeastern boundary of the Gurvansaikhan terrane (Porter T.M et.al., 2016; Badarch et.al., 2005). This study area is predominantly comprised of Carboniferous island arc volcanic and plutonic rocks where occur in center part of the Mandakh area. Also, the oldest complexes that are Paleoproterozoic to Mesoproterozoic relatively a small amount of distribution of metamorphic rocks occur in the south eastern part of this survey area.

Chapter II was considered about magmatic rock petrographic and geochemical character that Late Devonian to Carboniferous igneous rocks (TS, BF, MA, DO, UD and SH) are calc-alkaline, magnetite-series, I-type and except for north part, igneous are close to adakite island arc type. All magmatic rocks in this study area are widely distributed, but petrochemical characteristics of Devonian and Carboniferous magmatic rocks are slightly different from each other. The Permian magmatic rocks have more alkalic and siliceous composition. Petrographic and geochemical characteristics of the Mandakh area indicate good possibility for new discovery of porphyry copper deposit, like Tampakan of adakite type. It implies that magmatic rocks source in Mandakh area may be melting subduction slab from deep storage.

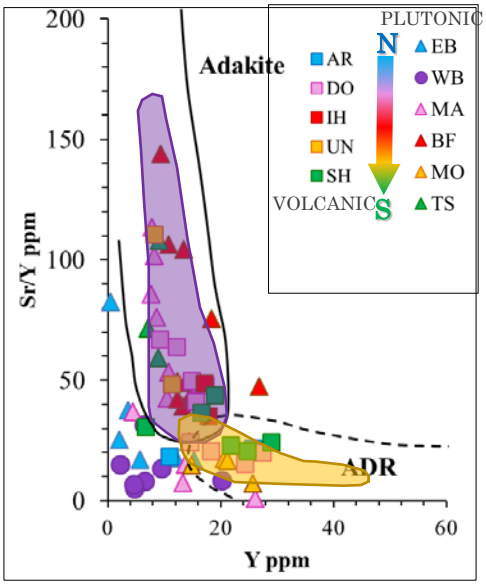

Fig. 1.a. Sr/Y-Y plot for rocks of the Mandakh area TTD: trondhjemite-tonalite-dacite, ADR: andesite-dacite-rhyolite.

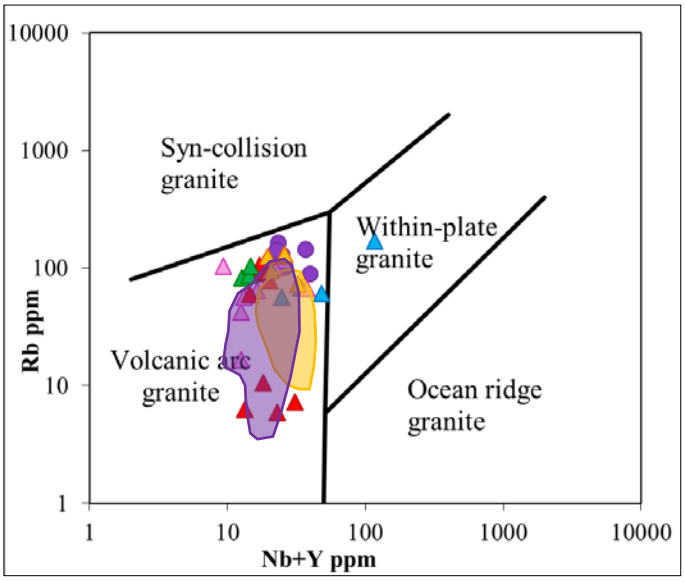

Fig. 1.b. Rb-(Nb+Y) discrimination diagram for the Mandakh area (after Pearce et al., 1984)

Chapter III. Mineral assemblage and P-T condition of the metamorphic rocks in Mandakh area.

The Norovzeeg and the KhutagUul metamorphic complex occur in the southeastern part of the Mandakh area. In the Southeast small part of the Mandakh and Khonichiin Ovoo area include Paleo-Proterozoic the Khutag-Uul formation (PPhu), Meso-proterozoic the Norovzeeg formation (MPno), Neoproterozoic Kharangad intrusion, Jurassic the Khamarkhuvur sedimentary formation and Cretaceous sedimentary rocks and Quaternary sediments. I focused on only metamorphic formation which are the Khutag-Uul (PPhu) metamorphic complex and the Norovzeeg (MPno) complex in the Mandakh area. These metamorphic complexes are identified as Paleoproterozoic and Mesoproterozoic by previous researchers and comprise of mafic- felsic gneiss, amphibolite and meta-volcanic rocks. Fifty thin sections were analyzed under petrographic analysis, but seventeen samples were determined by EPMA technique, which samples included minerals that can be estimated P-T condition.

The P-T conditions are determined based on following tree different mineral assemblages:

- mineral assemblage 1 comprises of clinopyroxene, garnet and plagioclase,
- mineral assemblage 2 contain amphibole and plagioclase,
- mineral assemblage 3 is consisted of garnet, biotite, plagioclase and quartz.

This chapter will explain P-T condition of the KhutagUul and Norovzeeg metamorphic complex used three different mineral assemblage which are Garnet+Plagioclase+Biotite+Quartz (felsic gneiss with garnet), Amphibole+Plagioclase (amphibolite) and Clinopyroxene+Plagioclase+Garnet (mafic gneiss with garnet). Mafic gneiss yields maximum P-T condition which is 6.4 kbar at 800 °C, whereas felsic gneiss referred minimum P-T condition that is 0.5 kbar at 550 °C. In the Mandakh and Khonichiinovoo survey, metamorphic rocks yield prograde metamorphism proceeds under hornbels through amphibolite and granulite phases.

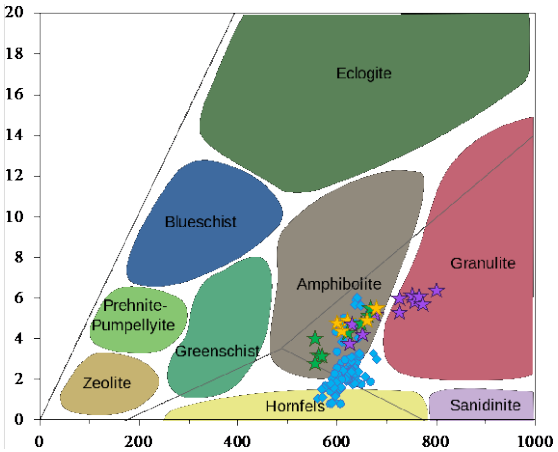

Fig.2. Discrimination of the P-T path for felsic gneisses (blue color points) and mafic gneisses (stars) which contain garnet grains showing prograde metamorphism under hornfels to amphibolite phase and amphibolite to granulite phases, respectively.

Chapter IV. Geochronological analysis of magmatic and metamorphic rocks in Mandakh area

Chapter IV involved explanation of geochronological evolution. Geochronological studies were conducted on magmatic and metamorphic rocks which are the Mandakh pluton (MA), the Bronze Fox pluton (BF), the West Budar pluton (WB), the Dushiinovoo formation (DO), the Sainshandkhudag formation (SH), the UndurUud formation (UN) and the KhutagUul complex, in order to link the evolution of petrochemistry and magmatic physic-chemical properties with geodynamic framework of Mandakh area in Southeastern Mongolia, CAOB. The $^{238}U/^{206}Pb$ zircon dating utilized by LA-ICP-MS. The oldest zircon grains were found from the KhutagUul metamorphic complex, which are Precambrian age. But, in the southeastern Mongolia, there isn't Precambrian microcontent basement, which these samples protoliths somehow respect to sedimentary rock. All igneous rocks zircons refer Carboniferous. But age is getting young to north in this study area. The KhutagUul metamorphic rocks timing of metamorphism suspected during Permian to Triassic, and magmatism and sinistral shear fault zone, respectively.

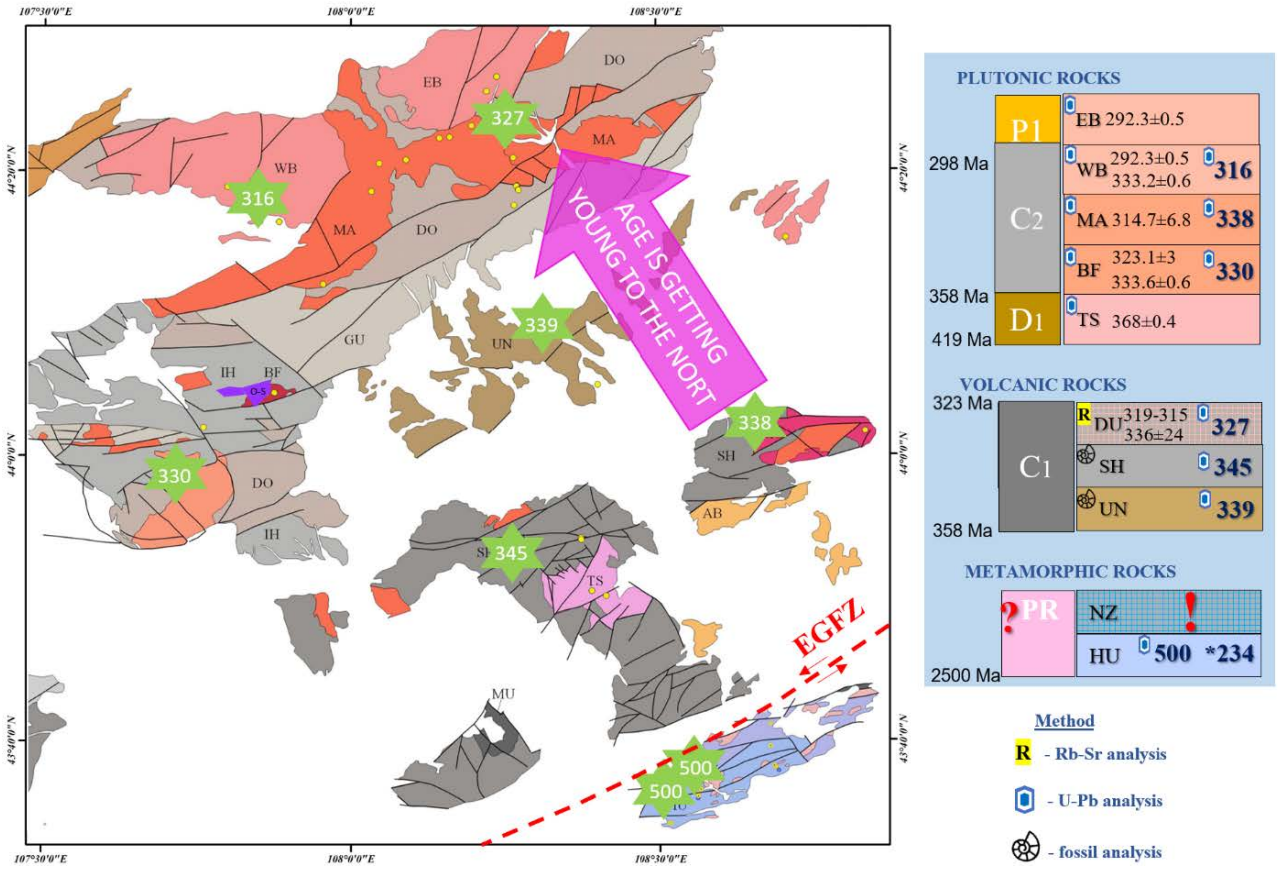

Fig.3. The geochronological results on the geological map shows that age is getting young to the north direction and comparation table displayed previous studies age (black) and new analyzed (bold dark blue) absolute age with analytical method from igneous and metamorphic rocks in the Mandakh area.

Chapter V. Paleozoic subductions of Mandakh area, south east Mongolia

In the chapter V is compared and integrated previous chapters result due to explain for tectonic evolution of Mandakh and Khonichiinovoo study area, in south Mongolia. There are several subductions were settled during various geological time. Precambrian time is somehow related with magmatic process. Then active continental arc developed in the Mandakh and Khonichiinovoo area during Ordivician to Silurian time. However, During Devonian to late Carboniferous, new warmer and deeper adakite-type island arc derived from slab melts in the Mandakh area. In addition, that time all of enriched porphyry copper deposits are created with magmatism. In this study area's tectonic evolution during the Late Carboniferous to the Permian, transition zone that is moved from adakite to non-adakite type and active continental island arc were developed southeastern Mongolia. In the Triassic, the KhutagUul and Norovzeeg metamorphic complex were moved and metamorphosed by the East Gobi Fault Zone.

（別紙）

論文審査結果の要旨及びその担当者

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論　文　題　目	**Petrology, Geochemistry and Geochronology of Paleozoic Granitoids and Metamorphic Rocks in Mandakh Subduction Zones, Southeastern Mongolia　(モンゴル国南東部 Mandakh 沈み込み帯における古生代花崗岩類と変成岩類の岩石学，地球化学ならびに年代学に関する研究)**
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論文審査結果の要旨

モンゴル国南ゴビ地方は，斑岩銅鉱床を主体とする豊富な鉱物資源の賦存地域であり，同国の主要産業である鉱業の代表地域のひとつとなっている．また，南ゴビ地方は，中央アジア造山帯（CAOB）の重要な位置を占め，この地域の地質構造発達史の解明は，モンゴル国のみならず，中国北部域，さらにはユーラシア大陸の形成を理解するための重要な地域のひとつである，本地域の地質調査は，1950 年代後半から行われているが，地球化学，年代学などを合わせた総合的な解明は十分でなく，本地域が沈み込み帯を形成していることは指摘できても，詳細な地史を編むことはできていなかった．本研究は，モンゴル国南東部 Mandakh 地域の火成岩類，変成岩類についての地球化学ならびに年代学に関する研究から本地域の地質発達史を解明した研究で，全編 6 章よりなる．

第 1 章は緒論であり，本地域の地質学的特徴と研究手法についてまとめ，本研究の目的を述べている．

第 2 章は，Mandakh 地域に分布する，火山岩類，深成岩類の産状，岩石記載および全岩化学組成の分析から，火山岩類と深成岩類の分類や化学的特徴を明らかにし，本地域の南東部は，アダカイト的特徴を示す島弧であること，これが遷移帯を経て北西部においては火山弧の特徴を示すようになることを明らかにした．本研究の基礎となるきわめて重要な成果である．

第 3 章は，Mandakh 地域南部の Khonichiinovoo 地域に分布する変成岩類の岩石記載，鉱物共生関係と地質温度計，地質圧力計を用いた変成温度，圧力の推定を行い，本地域の変成岩類が，角閃岩相からグラニュライト相に至る変成作用を被っていること，組織解析からこれらの変成岩類には埋没期の経路(prograde path)が記録されていることを明らかした．当該地域の変成岩に対して初めて具体的な変成条件を明らかにしたもので，これは本研究の有用な成果である．

第 4 章は，Mandakh 地域の深成岩類，変成岩類について，LA-ICP-MS によるジルコンの U-Pb 年代を明らかにしている．この結果，本研究で対象とした深成岩類は，いずれも石炭紀の活動であり，さらに南西部から北東部にかけて系統的に若くなることを明らかにした．従来の年代値は，相互的関係が曖昧で，また正確さを欠いていたが，本研究により，明確な年代値を得ることができた．これは，本研究を支える重要な成果である．

第 5 章は，岩石組織的特徴，岩石化学的特徴ならびに年代値を考慮して，本地域の新たな地質発達史を提案している．本地域は，カンブリア紀に沈む込み帯が形成され，その後，石炭紀前期に，アダカイト質深成岩を形成，海溝自体が徐々に南下し，また沈み込む角度も低角に推移したことを示している，さらに三畳紀に大規模な横ずれ断層を伴う地塊の衝突が生じて，深部地塊が上昇したと推定した．本地域には，多くの斑岩銅鉱床があり，今後この地質構造発達史を基礎として，鉱床形成の解明が行われることが期待される

第 6 章は，結論である．

以上要するに．本論文は，モンゴル国南東部 Mandakh 地域の火成岩類と変成岩類の岩石学解析と地質時代論から，当該地域は，古生代，特に石炭紀の沈み込み帯において火成活動が発生し，その火成活動の場は系統的に変化していることから鉱床形成の場の制約を明らかにしたもので，地質学ならびに環境科学の発展に資するところが少なくない．

よって，本論文は博士(学術)の学位論文として合格と認める．